

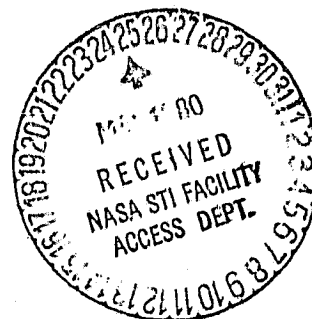
## N O T I C E

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OF ENERGETIC PARTICLES, 1-5 AU Final  
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CORONAL MAGNETIC STRUCTURE AND THE LATITUDE AND LONGITUDE  
DISTRIBUTION OF ENERGETIC PARTICLES,  
1-5 AU



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### ABSTRACT

We present the methods, conclusions and resulting recommendations of a study relating coronal magnetic field structure to the distribution of  $\sim 1$  MeV protons in interplanetary space between 1 and 5 AU.

After ordering the interplanetary data by its estimated coronal emission source location in heliographic coordinates, we compared the multi-spacecraft measured proton fluxes from IMP-7/8 at 1 AU and Pioneers 10 and 11 in deep space with coronal magnetic field structure inferred from American Science and Engineering Skylab soft x-ray photographs and Harvard College Observatory potential field calculations. We find evidence for the propagation and possible acceleration of solar flare protons on high magnetic loop structure in the corona, and we show that corotating proton flux enhancements are associated with regions of low coronal x-ray emission (including coronal holes), usually in association with solar wind stream structure, in agreement with previous studies linking solar wind velocity streams with both corotating proton enhancements and coronal holes.

#### Key Words:

Coronal magnetic fields, interplanetary  
 $\sim 1$  MeV proton distribution, propagation

## I. INTRODUCTION

We undertook an analysis of the interplanetary distribution of energetic charged particles and its relation to the large-scale coronal structure observed during the Skylab mission. We have carried out this original task and obtained significant new results on the propagation of energetic particles through the solar corona after acceleration in flares.

To a greater degree than we anticipated, we were also able to analyze particle flux gradients as a function of heliolatitude, finding good association with the coronal features which are identifiable with sources of high speed solar wind streams. We were able to extend this analysis some 20 solar rotations beyond the Skylab period with the use of Pioneer-10 and 11 particle and plasma measurements.

Our efforts were assisted at JHU/APL by J. M. Hansen and by the gracious cooperation of A. S. Krieger and D. F. Webb of American Science and Engineering, R. H. Levine of Harvard College Observatory, and P. S. McIntosh of the National Oceanic and Atmospheric Administration.

## II. METHOD

In this study we have ordered the measurements of particles and solar wind plasma in a natural heliographic coordinate system to enable us to make direct comparisons with the observed coronal structure. We mapped interplanetary energetic particle fluxes and magnetic fields from time ordered sequence into the heliographic latitude and longitude of their sources in the high corona by assuming that the solar wind flows radially from the high corona with negligible acceleration in interplanetary space (*Nolte and Roelof, 1973a, 1973b*), and that the energetic particles are constrained to propagating along the "frozen-in" interplanetary magnetic field (*Zwickl, Roelof and Gold, 1979*). By this technique, we could compare particle measurements from a given spacecraft directly with the spatial structure in the corona (as observed in soft x-rays,  $H\alpha$ , and potential field calculations), at the foot point of the large-scale interplanetary field line from the spacecraft. Since we also had data from deep space (Pioneer 10 and 11),

we could also compare the particle fluxes from points widely separated in longitude, latitude, and radius (Figure 1). Therefore, whenever the particle distributions were quasi-stationary on the time scale  $\sim 10$  days, we could also examine the flux gradients in radius and latitude between the earth and the Pioneers.

Coronal x-ray emissive loop structure was mapped into heliographic latitude-longitude charts from photographs taken on Skylab by the American Science and Engineering soft x-ray telescope (*Hanson and Roelof, 1979*) and these charts were further refined and upgraded through examination of high-quality second-generation internegatives at American Science and Engineering.  $H\alpha$  Synoptic Charts of chromospheric absorption features (*McIntosh, 1979*) were also used as indicators of coronal structure, and potential field calculations carried out at Harvard College Observatory (*Levine, 1977*) were employed to help indicate the location of open magnetic field lines connecting from the low to the high corona. In addition, solar activity charts were prepared for rapid identification of the long-term time history of active regions at given heliographic longitudes (*Hanson, Roelof and Gold, 1979*).

### III. RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

The study fell naturally into two categories: (i) impulsive particle events; and (ii) corotating (recurrent) particle enhancements.

(i) Impulsive particle events during the Skylab period are described in a paper prepared for submission (preliminary results reported to the American Geophysical Union: *Mitchell, Roelof and Hanson, 1979*). The propagation of flare accelerated protons from the  $H\alpha$  flare site to the point of escape onto interplanetary field lines is related to coronal bright x-ray loop structure. It is found that continuous x-ray loop structure between the flare site and the inferred open field line region (inferred from HCO potential field calculations) is a necessary condition for the access of flare accelerated protons to the interplanetary field whose source lies in the inferred open field region (Figure 2). Furthermore, for those flares for which continuous x-ray bright loop structure exists between the flare site and the inferred connection point of the magnetic field measured in interplanetary space

by a spacecraft, a correlation is shown in Figure 3 between the peak  $1-8\text{\AA}$  x-ray flux measured by Solrad and the peak  $\sim 3$  MeV proton flux measured on IMP-7/8. It is also shown that no measurable fluxes are detected when the inferred connection point in the low corona lies within  $15^\circ$  heliographic of the flare site, during the Skylab period. We suggest from this study that flare accelerated protons propagate along high-lying magnetic loops in the corona, and that these loops may represent the acceleration region of the particles as well as the propagation route. We also conclude that the number of relativistic electrons accelerated is directly related to the number of  $\sim 3$  MeV protons accelerated based on the  $1-8\text{\AA}$  x-ray result.

*Recommendation:* This work could be extended to include a longer time base, with the use of closed loop potential field calculations to indicate coronal magnetic field structure, and using the x-ray loop structure during the Skylab period to determine the applicability of the potential field calculations to this type of study. In particular, the further investigation of those flares with  $< 15^\circ$  separation from inferred open field sites should be extended to other periods for verification or size of flare threshold effects, as all those flares fitting this criterion during the period covered in this study were small.

(ii) Corotating recurrent particle enhancements, both during and subsequent to the Skylab period have been analyzed and preliminary results reported by *Mitchell and Roelof (1979)*; a manuscript is being completed for submission for publication. In this work, it was found that when spacecraft lie along the same interplanetary magnetic field line, we rarely observe significantly differing fluxes (i.e., field-aligned gradients) in corotating enhancements (Figure 4) whereas when the spacecraft lie along field lines with the same connection longitude but different connection latitudes they often measure significantly different fluxes (Figure 5). From this we conclude that the flux differences observed between the Pioneer spacecraft and earth, previously described solely as radial gradients (*Van Hollebeke et al., 1978*), may often actually be due mainly to latitudinal gradients (Figures 6 and 7).

The source of these corotating enhancements remains uncertain, though there is good evidence that they are at least in part the result of stream-related interplanetary acceleration processes. It also appears that particles accelerated in the corona during flares often populate these regions initially, whereas solar wind and coronal morphology may dominate the distribution and possible re-acceleration of these particles in the quasi-steady-state following the decay of a flare. In a refinement to the work of *Barnes and Simpson (1976)*, who related corotating enhancements to stream structure, we find in our study spanning 40 solar rotations frequent association between previously detected solar wind velocity latitudinal gradients (*Schwenn et al., 1978; Mitchell, Roelof and Wolfe, 1979*) and  $\sim 1$  MeV proton flux gradients.

...

In examining the relationship between the distribution of corotating enhancements and coronal x-ray emissive structure from the S-054 Skylab photographs, we find the primary correlation to be the enhanced particle flux levels mapping back to coronal holes. This is in agreement with the previously mentioned association of corotating enhancements with solar wind streams coupled with the well-known relationship linking high speed solar wind streams during Skylab with coronal holes. Thus the latitudinal and longitudinal distribution of the interplanetary corotating proton enhancements is correlated with the distribution of coronal holes in the solar corona. Furthermore, there appears from this work to be a general association between corotating proton flux enhancements and coronal regions devoid of x-ray emissive loop structure (including coronal holes), even in those cases when there is poor or ambiguous association with solar wind stream structure.

*Recommendation:* This study could also be extended by using HCO closed-loop potential field calculations. However, more work can be done even during this period, but working with higher time resolution data, including hourly averaged (or better) Pioneer-11 solar wind plasma and interplanetary magnetic field measurements. In this way, individual events of interest could be studied in greater detail and present ambiguities in the 6-hour data between spatial and temporal structure might be resolved.



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## APPENDIX

### CORONAL PROPAGATION OF $\sim 1$ MeV PROTONS AND CORONAL MAGNETIC FIELD STRUCTURE DURING SKYLAB

D. G. Mitchell

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J. M. Hanson (all at: The Johns Hopkins Univ.  
Applied Physics Lab., Laurel, Maryland 20810)

Energetic ( $\sim 1$  MeV) proton measurements from IMP-7 & 8 (JHU/APL, GSFC) and Pioneers 10 and 11 (GSFC/UNH) are used to identify the coronal magnetic field structures which control the coronal propagation of flare-associated protons. Particle emission longitudes and latitudes are deduced from the high coronal foot-points of interplanetary field lines estimated from solar wind speeds measured on each spacecraft. Closed coronal magnetic field structures are inferred from x-ray emission structure seen in photographs from the American Science and Engineering soft x-ray imaging telescope on Skylab, while open field structures are identified from the potential field calculations analyzed by Levine (*Astrophys. J.*, 218, 291, 1977). Flare associated particles are preferentially emitted from source regions of open coronal field lines from which complexes of emission loops lead back to the flare site. No particle event was detected when there is a  $\geq 10^\circ$  break in the x-ray loop structure between the flare site and the open field source region, or when the flare site is quite near ( $< 15^\circ$ ) the open field source region. The former condition is consistent with coronal particle propagation via contiguous high lying loops followed by escape from a source region of open field lines, while the latter condition paradoxically implies that escape from the immediate vicinity of the flare site (if indeed that is the particle acceleration site) is inhibited when there is a nearby region of open field lines. For the particle events with good connection via complexes of x-ray loops in the corona between the flare site and the open field source region, the peak flux is correlated with the 1-8 Å SOLRAD x-ray intensity of the flare, suggesting that the particle escape probability does not depend strongly on the details of the structure of the high loop complexes.

1. 001730 ROELOF
2. 1978 Fall Meeting
3. SS (Solar and Interplanetary Physics)
4. None
5. No
6. No
7. None
8. The Johns Hopkins University  
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## APPENDIX

### LATITUDE DEPENDENCE OF $\sim 1$ MeV PROTON FLUX MEASURED 1-5 AU

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We examine measurements of non-impulsive  $\sim 1$  MeV proton flux increases from instruments aboard IMP 7 and 8 and Pioneer 10 and 11 for possible latitude dependence. The measurements include published data from Goddard Space Flight Center, University of Chicago, and JHU/APL detectors and cover Carrington Rotations 1600-1613, 1615-1620, 1622-1626, and 1636-1640. This data set therefore contains many of the "co-rotating" particle events associated with recurrent solar wind streams. The fluxes are compared by ordering them according to the estimated heliographic longitude and latitude where the interplanetary magnetic field line traces back to the sun under the assumptions that the measured solar wind velocity is constant and radial, and that the magnetic field is "frozen-in". During Rotations 1600-1603, the fluxes either agree at the IMP and Pioneers, or are dominated by temporal flux increases. From 1608 to 1613, as the radial and latitude separations between the earth and Pioneers grow, the differences in distributions of particle flux increase. Some of the flux differences are likely related to latitude structures found previously in solar wind velocity at this time. During Rotations 1615-1620, when the spacecraft lie at nearly the same heliographic latitude, there is agreement among flux levels which, however, is disrupted by large flares on Rotations 1616 and 1619 when a positive field-aligned gradient is apparently set up in the decay phase of the flare events. On Rotations 1622-1626, as the heliolatitude differences between IMP and Pioneer 11 increase once again, the fluxes become decorrelated, with one recurrent event being larger at Pioneer 11, while another (originating  $180^\circ$  around in heliolongitude) is consistently larger at Earth.

1. 029813 MITCHELL
2. 1979 Spring Meeting
3. Cosmic Rays (SC)
4. Transport of Energetic Particles in the Heliosphere
5. No
6. No
7. 0%
8. Applied Physics Laboratory  
The Johns Hopkins University  
Laurel, Maryland 20810

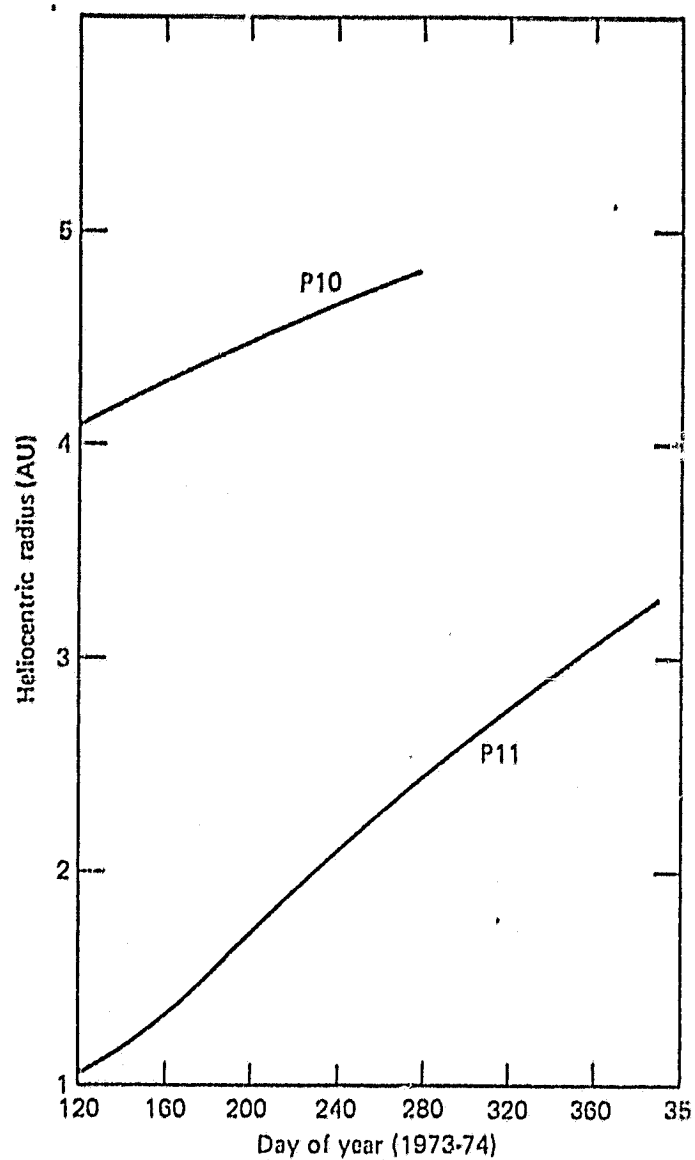
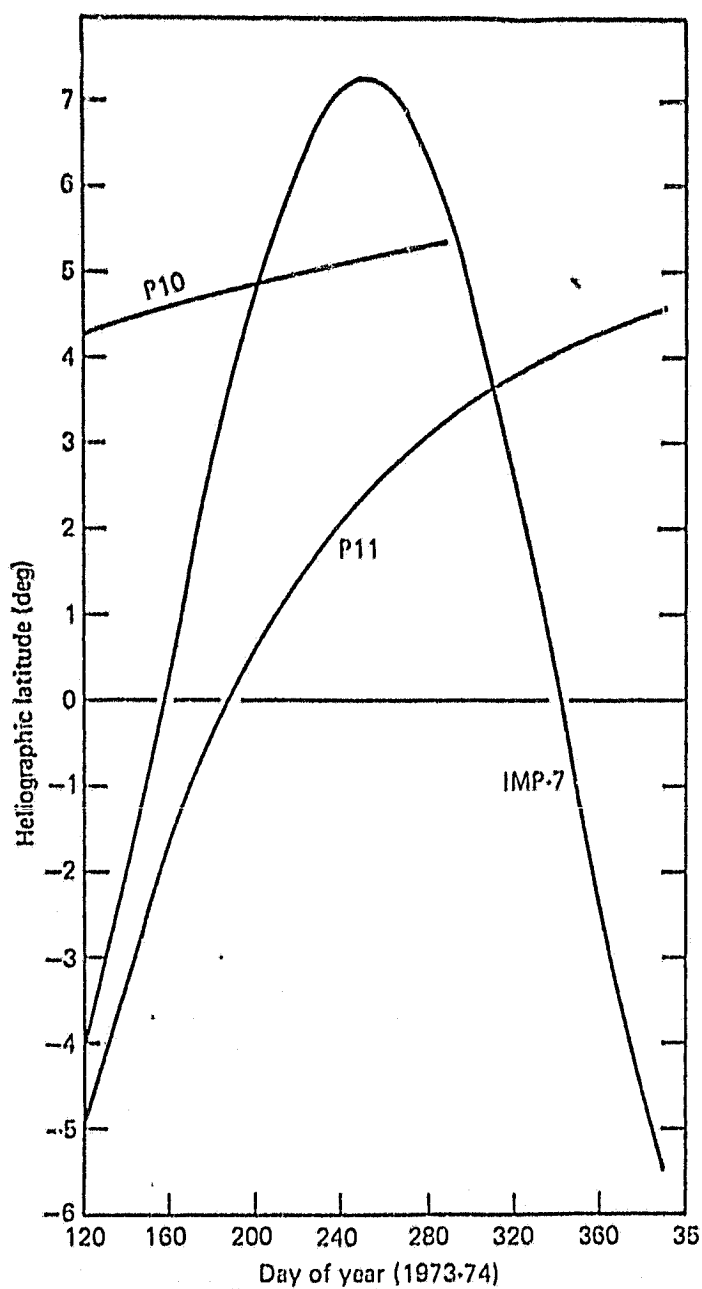


Figure 1

*Trajectories of the spacecraft included in this study.*

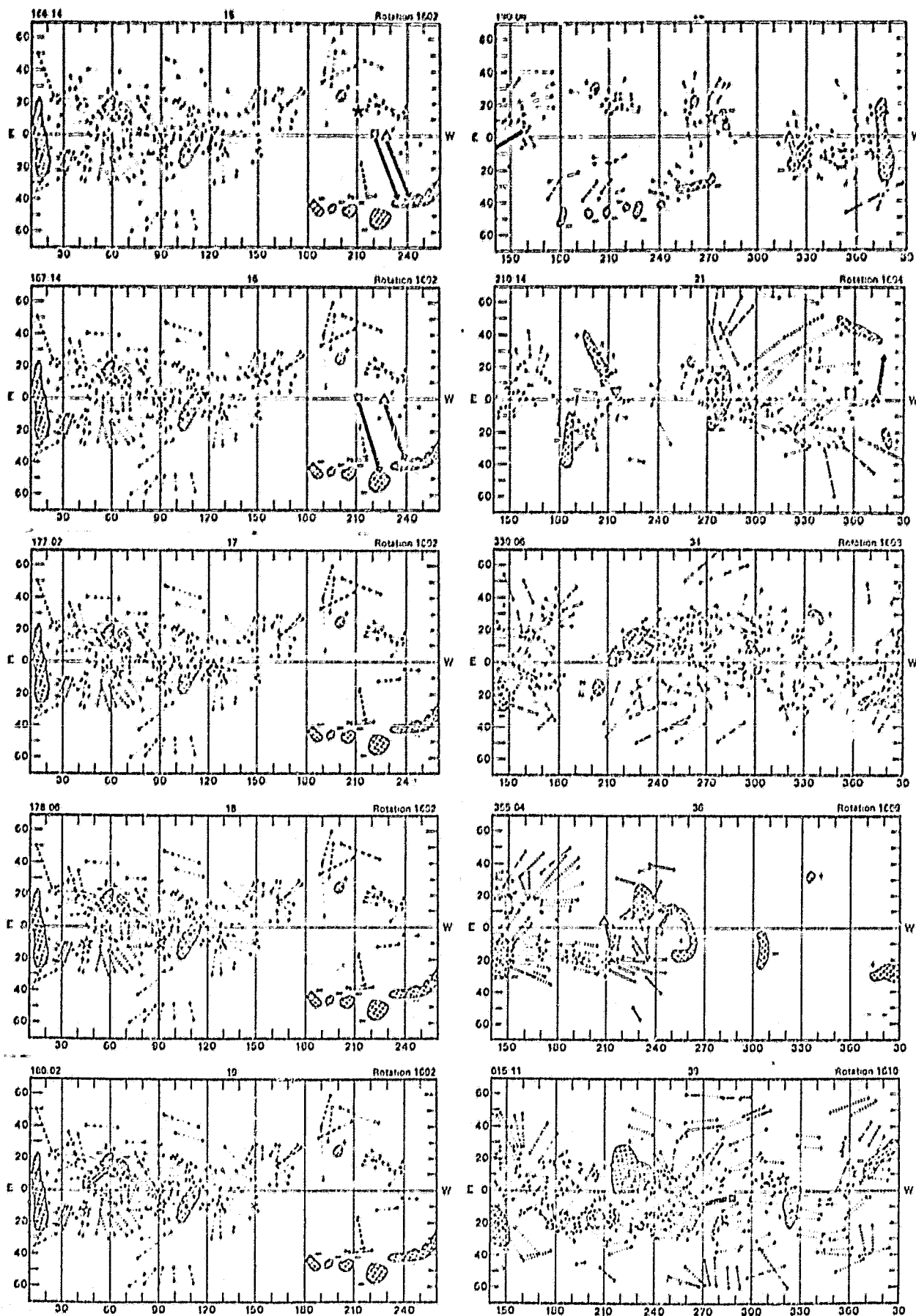


Figure 2.

A series of flares plotted on heliographic synoptic charts, including bright x-ray loops (dots connected by dashed lines), flares (stars - larger stars are larger flares, open stars are F or N, closed are B), open field sources (cross hatched), coronal holes (grey shade), x-ray plages (finely hatched) and arrows from spacecraft symbols (square is earth, triangles are Pioneers) to their open field sources. Open spacecraft symbols indicate no measured impulsive fluxes, filled indicate flare protons measured.

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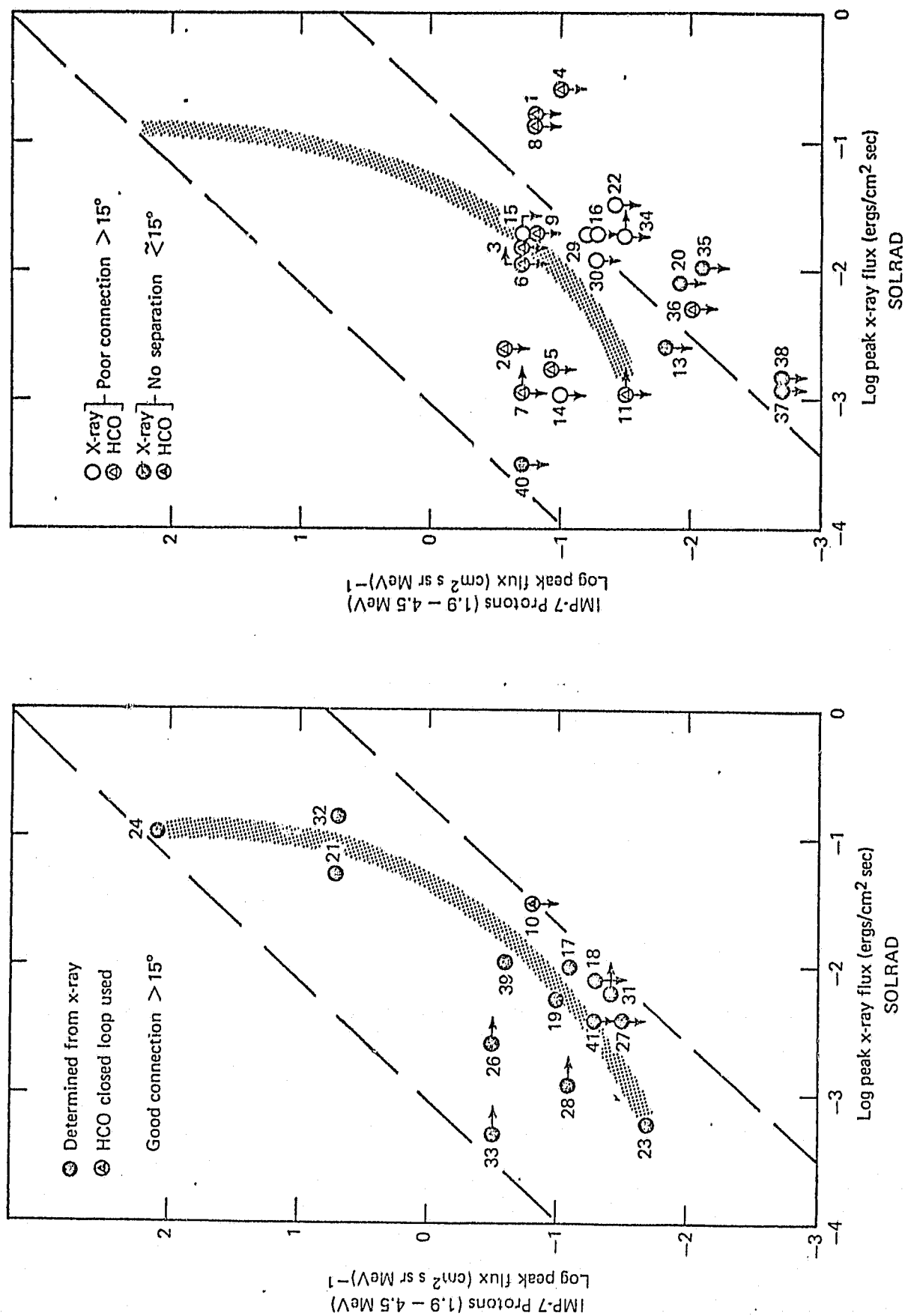


Figure 3

Peak proton flux vs. peak 1-8Å x-ray flux. For those flares in Figure 2 (and others not shown) which are well connected via bright x-ray loops in the corona, the x-ray flux correlates with the proton flux, while for those flares with poor connection or  $<15^\circ$  separation from the open field line source, no correlation is apparent. Horizontal arrows indicate lower limit in x-ray flux, vertical arrows indicate upper limit in impulsive proton flux (symbol lies at ambient proton flux level).

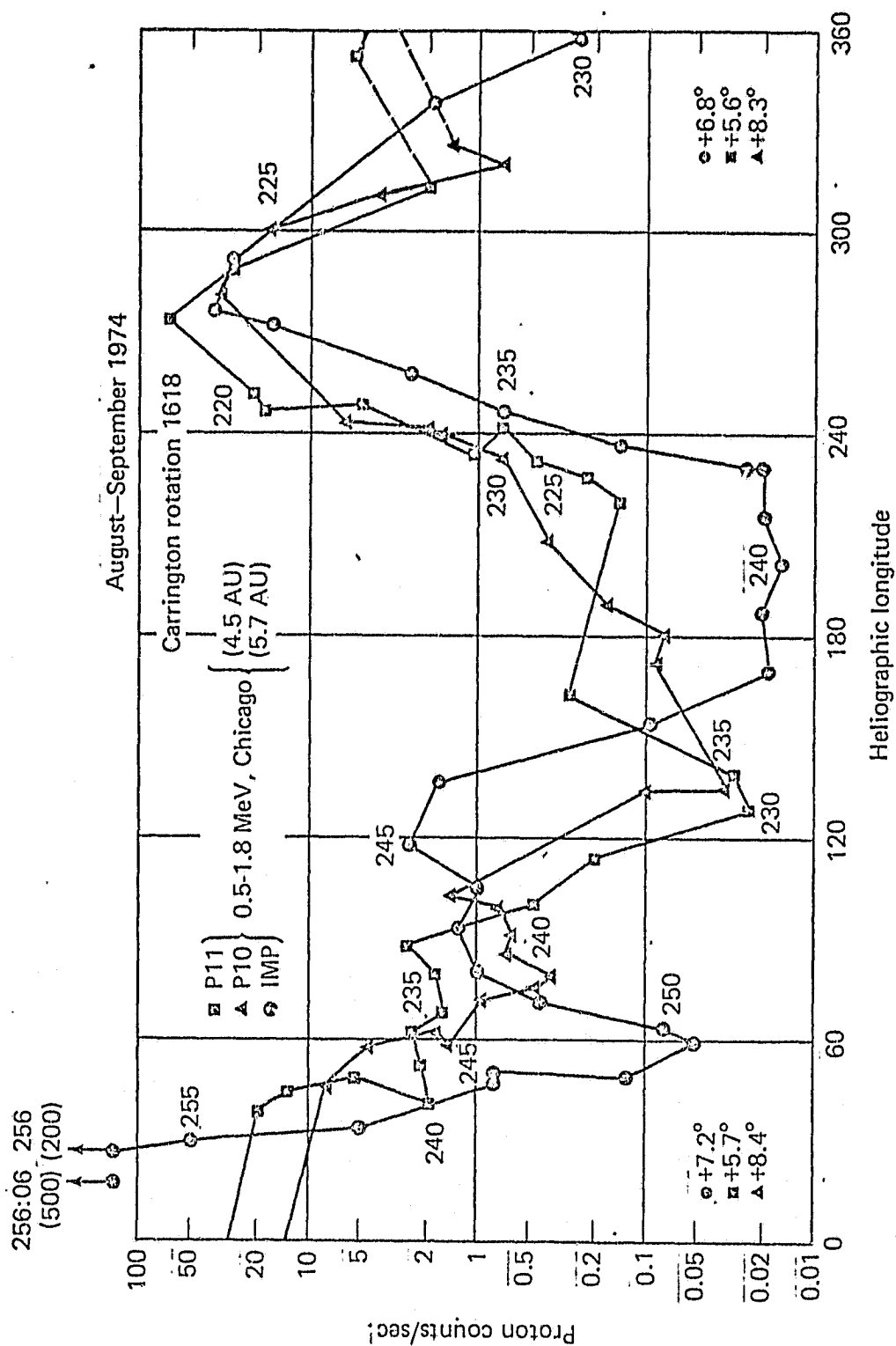


Figure 4

Count rates of  $\sim 1$  MeV protons mapped in heliographic longitude. Note the agreement in the peak of the enhancement at  $\sim 280^\circ$ , where the latitudes (indicated at either end of the rotation) do not differ significantly. This indicates the absence of a field-aligned gradient.



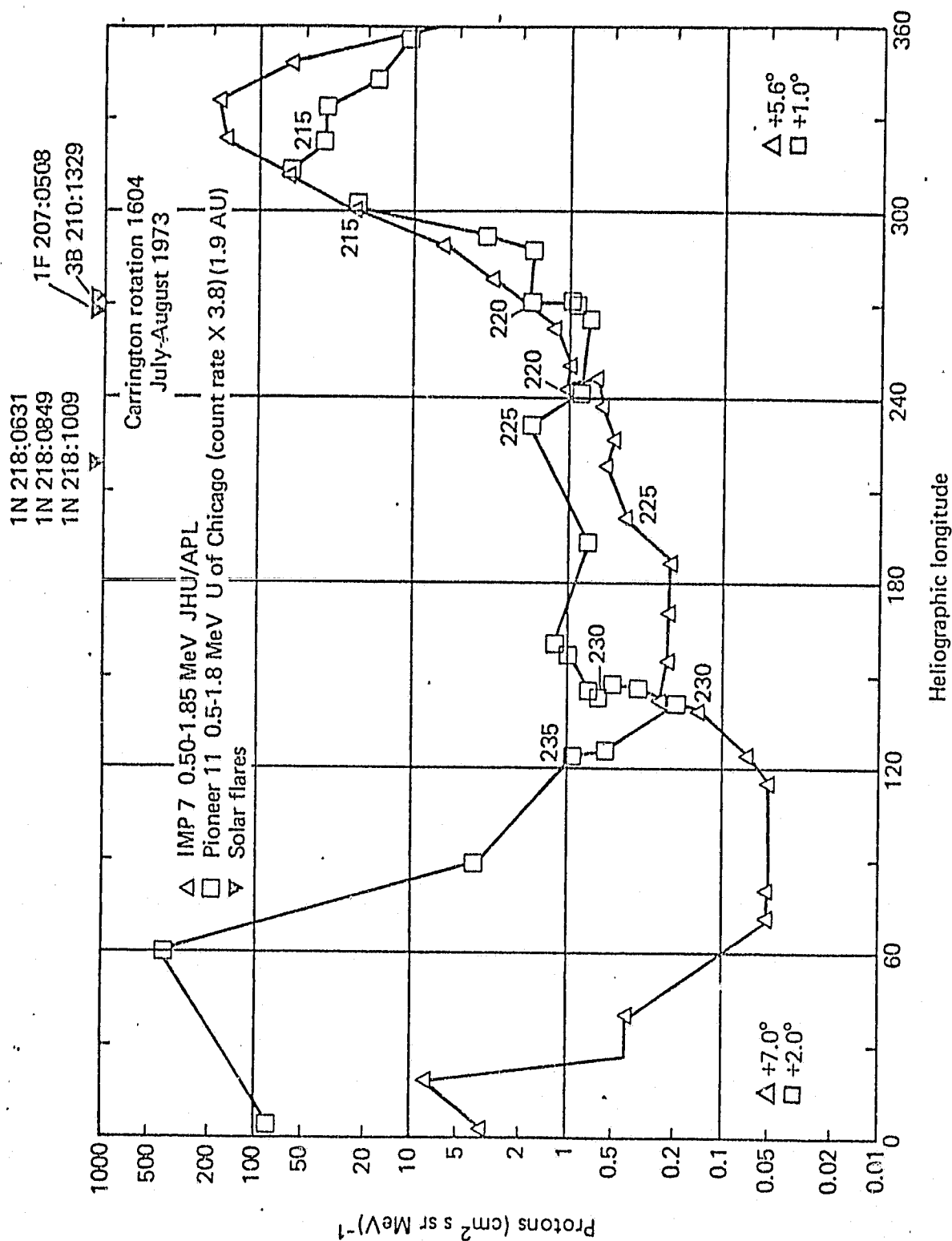


Figure 5

Fluxes of ~ 1 MeV protons mapped as a function of heliographic longitude. The fluxes differ widely at some longitudes, but at a 4 to 5 degree latitude separation these differences cannot be strictly radial or field aligned.

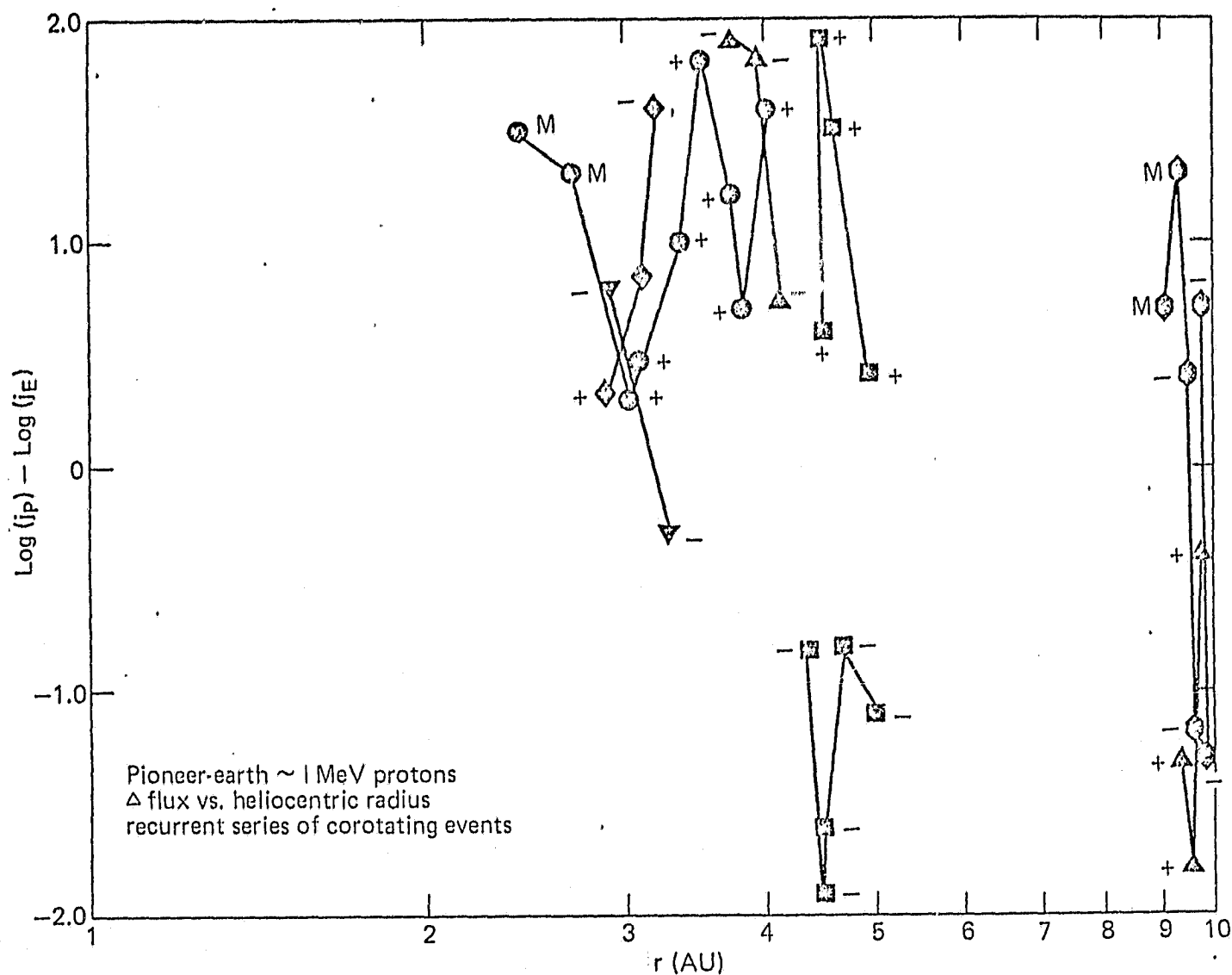


Figure 6

Differences in the logarithm of the  $\sim 1$  MeV flux levels between Earth and Pioneer-10 or Pioneer-11, plotted as a function of radius difference. Similar symbols connected by lines represent a sequence of corotating recurrent enhancements. Note that there is no systematic gradient as a function of radius, and that negative gradients appear as well as positive gradients, sometimes changing sign within a recurrent series.

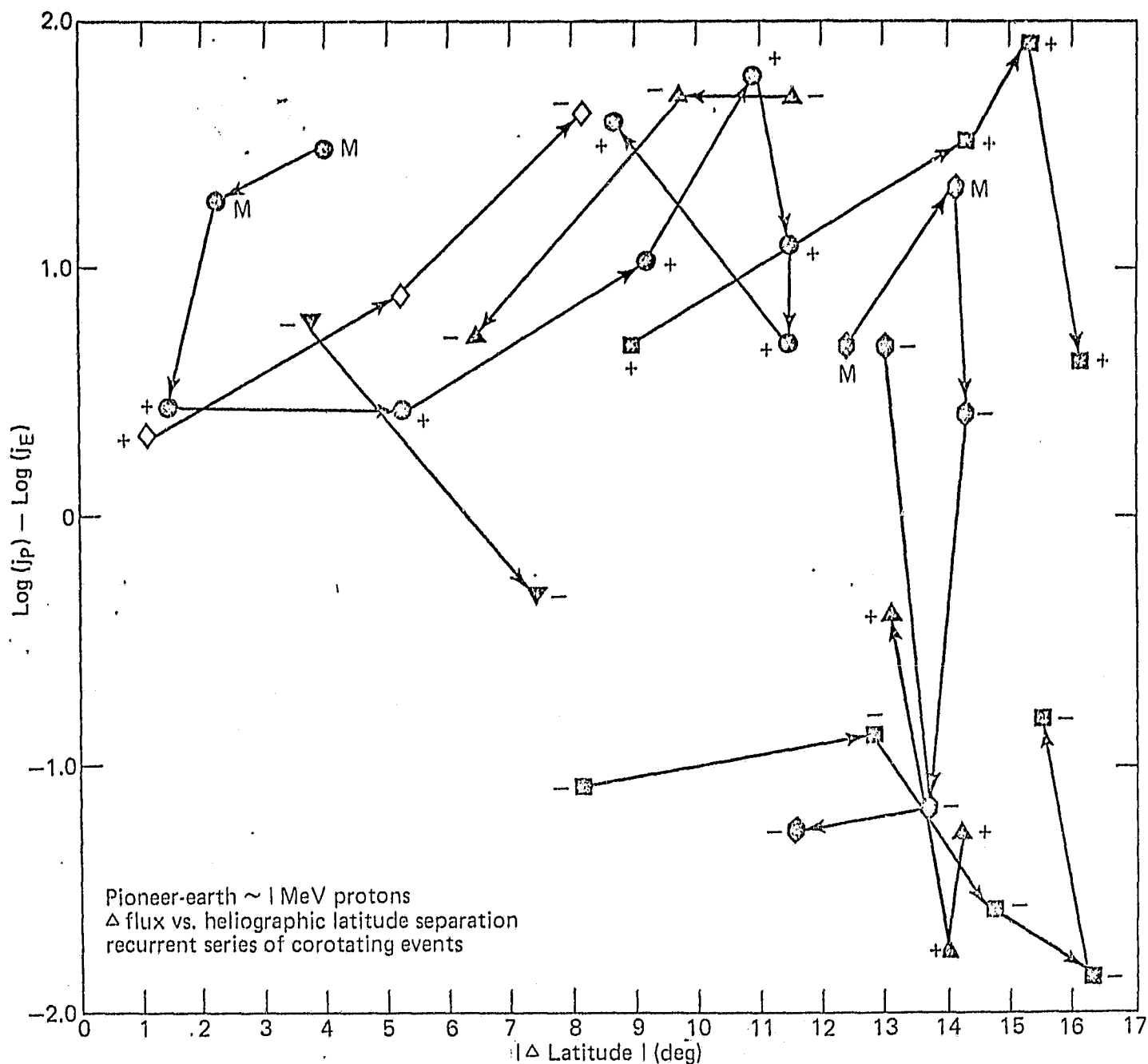


Figure 7

*Difference in logarithm of the  $\sim 1$  MeV proton flux between Earth and Pioneer-10 or Pioneer-11, plotted as a function of latitude difference. There is no systematic trend apparent, and gradients can be either positive or negative with latitude difference.*